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EVALUATION OF CRACK AND CORROSION DETECTION SENSITIVITY USING PIEZOELECTRIC SENSOR ARRAYS (PREPRINT)

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The use of guided-wave ultrasound has significant potential for structural health monitoring in a number of critical aerospace applications. A key question which needs to be addressed with regard to damage sensing in realistic aircraft structures involves detection sensitivity levels for cracks and corrosion. In this research effort, a systematic evaluation of the detection sensitivity levels of surface-bonded piezoelectric sensor arrays has been undertaken using experimental studies and analytic modeling. A series of reference standards have been developed for variations in crack/corrosion sizes and types from micron to millimeter scales. Both engineered and realistic crack/corrosion conditions have been studied using distributed sensing approaches. In-situ damage initiation and growth studies are also being conducted using dynamic fatigue crack and electrochemical corrosion attack damage mechanisms. Preliminary results are presented for evaluating typical damage detection levels, where opportunities for improving measurement fidelity, quantification, and sensitivity in realistic aircraft structures are considered.

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Evaluation of Crack and Corrosion Detection Sensitivity using Piezoelectric Sensor Arrays

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ABSTRACT

The use of guided-wave ultrasound has significant potential for structural health monitoring in a number of critical aerospace applications. A key question which needs to be addressed with regard to damage sensing in realistic aircraft structures involves detection sensitivity levels for cracks and corrosion. In this research effort, a systematic evaluation of the detection sensitivity levels of surface-bonded piezoelectric sensor arrays has been undertaken using experimental studies and analytic modeling. A series of reference standards have been developed for variations in crack/corrosion sizes and types from micron to millimeter scales. Both engineered and realistic crack/corrosion conditions have been studied using distributed sensing approaches. In-situ damage initiation and growth studies are also being conducted using dynamic fatigue crack and electrochemical corrosion attack damage mechanisms. Preliminary results are presented for evaluating typical damage detection levels, where opportunities for improving measurement fidelity, quantification, and sensitivity in realistic aircraft structures are considered.

INTRODUCTION

The detection of cracks and corrosion in aerospace structures using nondestructive evaluation methods has a long and well-established history [1,2]. In recent years, the development of integrated sensing approaches has become technically feasible in a number of situations where traditional nondestructive methods are difficult or impossible to implement [3-6]. The detection of hidden damage in complex geometry or inaccessible locations, for example, is currently a challenge for many legacy aircraft systems. As these legacy aircraft continue to age (some of the aircraft have been in service for 40+ years), hidden cracking and corrosion in critical load-bearing structures is becoming much more likely. Structural health monitoring (SHM) using integrated sensing approaches holds the promise for damage detection and structural integrity assessment in many of these critical remote location areas.

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A key aspect of any SHM measurement involves an accurate and reliable assessment of the health of the structure, which typically relies on detecting and quantifying strength-limiting damage features within the structure. For aerospace systems this damage typically involves cracks and corrosion in metallic structures, and disbonds and delaminations in composite structures. SHM is in a unique position to provide critical and timely information regarding the location, size, and orientation of damage sites within a structure, which can ultimately be used to determine residual strength levels and the remaining life of the aerospace system.

One of the most appealing and mature SHM sensing methods for aerospace structures involves guided ultrasound waves using distributed piezoelectric sensor arrays. Many advances have recently been reported using innovative phased-array [7,8], acoustic tomographic [9,10], and guided wave mode selection [11] approaches. Although some basic information regarding damage detection limits has been reported using these and other guided wave approaches, a much more comprehensive, standardized, and systematic evaluation of baseline sensitivity limits is needed. In this effort, such an evaluation has been undertaken with the expressed goal of establishing currently available damage sensing limits for cracks and corrosion in thin-walled metallic structures. The study is part of a larger SHM sensor validation effort which is focused on determining the fundamental performance, durability, and survivability characteristics of leading integrated sensor concepts for aerospace systems.

DAMAGE DETECTION USING SURFACE-BONDED PIEZO SENSORS

At its core, structural health monitoring (SHM) is often based on standard nondestructive evaluation (NDE) methods and procedures. For guided-wave ultrasound measurements using surface-bonded piezoelectric sensors, the well-established principles of wave mechanics, material science, and structural boundary conditions used in traditional NDE are equally important and applicable. A primary and significant difference does exist between SHM and NDE, however, with regard to how the damage is sensed and analyzed in real-world applications. NDE methods, for example, provide for user interactions and physical manipulation of the sensing probes, while integrated sensing methods involve stationary/fixed sensors and limited interaction and control of the system once it has been installed. Because NDE probes can be adjusted and manipulated during an inspection process, signal levels can be maximized by adjusting the location and type of sensing approach being used (e.g. frequency or angle of incidence adjustments). In contrast, integrated sensors are fixed in position, and cannot be changed significantly in how they are used once they are installed. This often places limits on the capabilities of SHM sensing approaches when traditional NDE data collection and analysis methods are used.

Integrated sensing approaches do offer two key advantages over NDE, however, which can have a significant effect on damage sensing capabilities. The use of differential sensing methods, where signals can be compared to a previously recorded baseline measurement, have been shown to provide improvements in sensitivity relative to nondestructive sensing methods [12,13]. SHM sensing methods also provide a unique capability for following and tracking damage over time, either continuously or intermittently. The other key advantage of integrated sensing involves the opportunity to monitor and track damage in the dynamic environment in which the

damage is accumulating. For metallic fatigue and crack damage, this permits damage accumulation to be coupled directly with usage information such as stress-strain and dynamic load conditions. Perhaps more importantly, however, the use of SHM sensing concepts provide the potential for cradle-to-grave assessments and the possibility of significant improvements in the early detection of damage.

At the most fundamental level, both SHM and NDE involve the indirect sensing of damage at some remote location by sending and receiving energy to and from a damage site. Figure 1 provides a simplistic diagram of a pair of piezoelectric sensors and a damage feature. Although very simple in nature, the situation depicted in Figure 1 helps to illustrate the basic measurement approach for a distributed piezoelectric sensing array. At the heart of the measurement is the transfer of mechanical energy from an actuation sensor and the reception of that energy by a receiving sensor. Perturbations or redirection of the energy provide information regarding the location and size of the damage site.

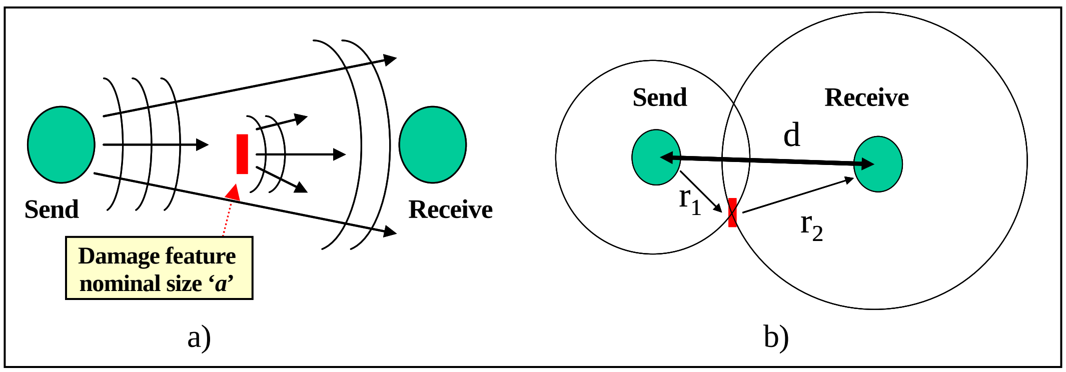
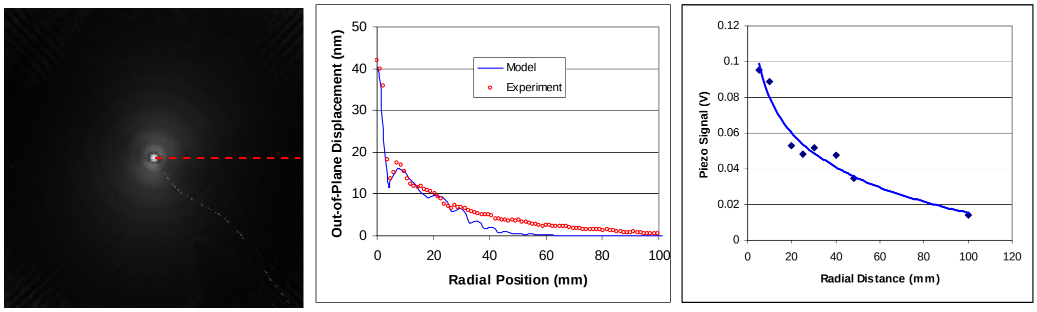


Figure 1. Basic sensing arrangement for a pair of piezoelectric sensor disks and a damage feature.

For the situation depicted in Figure 1, the send and receive sensors are thin piezoelectric disks which are adhesively bonded to the material substrate. This particular type of sensor introduces an omni-directional elastic wave into the material that expands radially into the material as shown in Figure 1b. Because the transmitted energy is continuously expanding, the available energy at any radial distance away from the excitation source decreases. This situation was observed experimentally and was later verified by finite element modeling, the results of which are presented in Figure 2. Figure 2a provides a displacement-field image [14] of the peak energy distribution radiating away from a circular piezoelectric disk (1 cm diameter, 200 micron thickness, 100kHz input pulse @ 10vPP), which has been bonded to a 1 mm thick aluminum plate. The decay of available energy is noticeable out to a distance of approximately 60 mm, where it tends to level off at a nominal value of approximately 10-15% of the energy level near the actuation source. Figure 2b provides finite element model results compared with the experimental data, while Figure 2c depicts signal levels for a pair of piezoelectric disks operating in pitch-catch mode with the receiver disk being bonded at increasing distances away from the source. The importance of this observation is that damage located at increasing radial distances away from the source excitation will have less energy available to scatter towards a receiving sensor, which will have an impact on the receiving sensor's ability to detect the damage.



a) b) c)

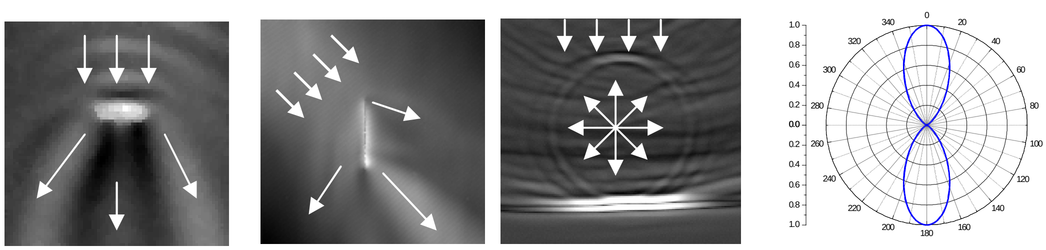
Figure 2. Energy distribution for a circular piezoelectric disk a) displacement-field image, b) experimental vs finite element model results, and c) pitch-catch signal reception for increasing radial separation distances.

For a nominal damage feature size of '*a*', the signal energy interaction for a radial distance of r_1 can be approximated as (long-wavelength regime $\lambda \le a$):

$$SignalEnergy \propto A_1 \frac{\phi_1}{2\pi r_1} = A_1 \frac{a}{4\pi^2 r_1^2}, \tag{1}$$

where A_1 is the signal amplitude output from the excitation source, and ϕ_1 is the intersecting arc for the damage at radial distance r_1 away from the source. Upon arriving at the damage site, the available intersecting energy distribution can reflect, scatter, redirect or otherwise perturb the energy as it propagates by. The ability of the receiving sensor to intersect the scattered energy field from the damage site, and provide a measurable signal, is similarly related to its distance away from the damage site as depicted in Figure 1b, following a similar dependency to Equation 1.

For the short-wavelength regime ($\lambda \ge a$), where the elastic wavelength is larger than the damage size, basic reflection, transmission, and mode-conversion processes are replaced by scattering, radiating, and diffraction processes, which tend to redirect the energy in dramatic fashions. Several examples of this are provided in Figure 3, which show displacement-field images of scattering patterns for small notches and cracks relative to the incident wavelength size. The importance of this is the basic fact that as damage becomes smaller the ability to detect, size, and locate the damage becomes a much more difficult task. The bi-polar scattering features depicted in Figures 3c and 3d provide evidence of the highly directional nature of elastic wave scattering processes which are typical for Lamb wave interactions in plate structures.

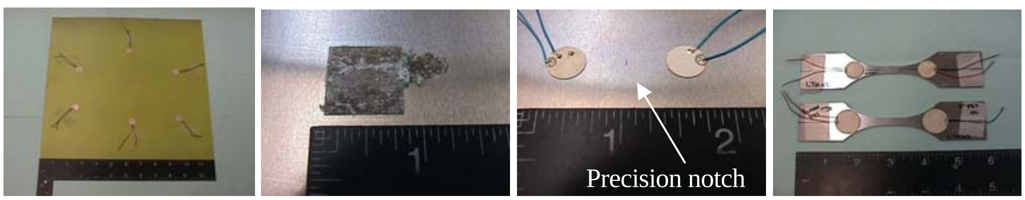


a) b c) d)

Figure 3. Scattering of energy by small damage features relative to the elastic wavelength a) normal incidence to 1mm notch, b) 45-degree incidence to 1mm notch, c) scattering from 300 micron surface-breaking crack, and d) calculated energy scattering plot for 300 micron surface-breaking crack.

EXPERIMENTAL STUDIES

A major goal of this effort was to understand the capabilities of surface-bonded piezoelectric sensor disks for detecting crack and corrosion damage features in thin metallic plate structures. In order to accomplish this, a number of reference standards were developed to provide simulated and realistic crack and corrosion features in the micron to mm size range. Figure 4 provides digital images of several of the sample types being used in the study. Realistic corrosion features were made using electrochemical etching processes and salt-fog exposure conditions. Simulated corrosion features were made using milled-out regions in the plates as well as through-the-thickness holes. An example of a salt-fog corrosion sample with piezoelectric sensor disks bonded to the back of the panel for in-situ measurements is depicted in Figure 4a. The corrosion feature generated during a 3-month salt-fog exposure test is depicted in Figure 4b.



a) b) c) d)

Figure 4. a) Salt-fog corrosion reference standard with bonded piezo sensors on the back of the panel, b) corroded region on the opposite side of the plate depicted in a, c) precision laser-machined notch feature with two bonded piezo sensors, and d) dynamic loading fatigue specimens with bonded piezo sensors in grip region of test specimen.

A series of precision machined notches were also fabricated to simulate surface-breaking cra.cks using a laser machining process with sizes ranging from 25 μm x 25 μm x 25μm to 25 μm x 2mm x 150 μm (width x length x depth). An example of one such notch is depicted in Figure 4c, where two piezoelectric sensor disks have been bonded at a distance of 1 cm from the damage site on either side. Realistic crack specimens are also being fabricated. One such means of monitoring crack initiation and growth processes is depicted in Figure 4d, where dogbone fatigue specimens have been produced with starter notches in the gauge region and a pair of surface-bonded piezoelectric sensor disks have been place in the grip regions of the specimens.

As mentioned previously, the possibility of conducting differential measurements for SHM applications provides a significant benefit relative to traditional NDE measurements. This is often a necessary condition for measurement success in the short-wavelength regime, where most Lamb-wave measurements associated with integrated sensors are made. Because Lamb-wave energy is distributed throughout the entire plate thickness, the use of pitch-catch and pulse-echo methods involve only limited damage interaction levels. An example of this situation is depicted in Figure 5, where the results for a differential measurement made for the small surface notch depicted in Figure 4c are depicted (25 μm x 2mm x 150 μm notch). Figure 5a provides a displacement-field image of the measured energy field distribution with the notch feature shown as a very minor increase in the displacement level as shown in the cross-sectional cut plot in Figure 5b. The plots in Figure 5c show before and after pitch-catch measurements (top) and a differential measurement (bottom).

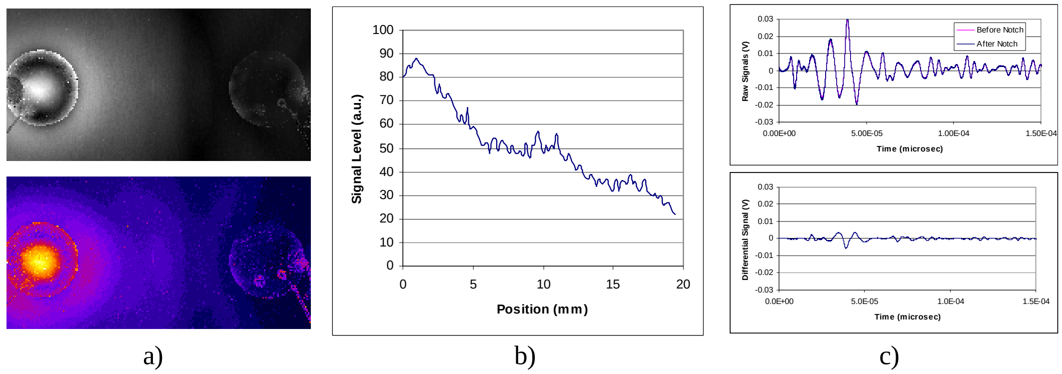


Figure 5. a) Displacement-field image of energy propagating from left actuation sensor to receiving sensor on right, b) cross-sectional cut of through centerline of the sensors showing drop in energy level with increasing radial distance away from actuation sensor and minor indication of notch feature at midpoint, c) receiver piezoelectric sensor signals overlaid for before and after notch (top plot), and differential signal obtained by subtracting the two plots (bottom).

The results depicted in Figure 5 show a very minor level of interaction of the raw signals with the small surface notch, but by using differential methods, the signal is measurable (in this case with a signal-to-noise ratio level of 2). Figure 6 provides an additional result that used differential measurements for increasing damage levels - in this case a thru-the-thickness hole which was increasing in size/radius. The sensors in this case were separated by a distance of 250 mm with the damage site located at the midpoint between the sensors.

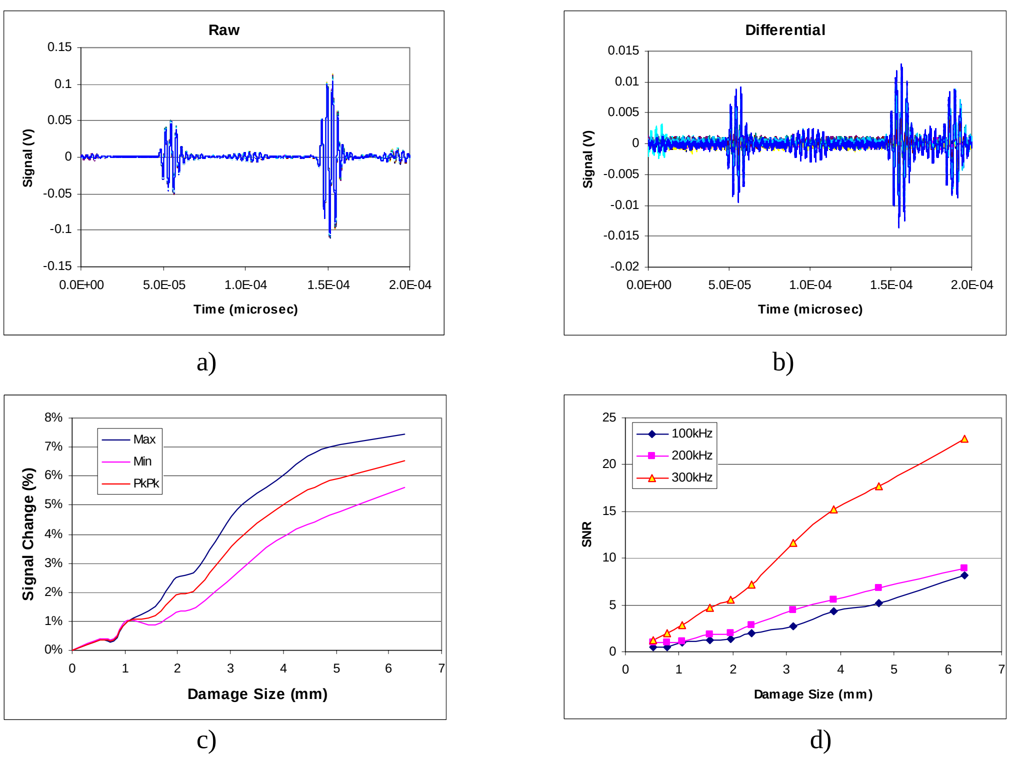
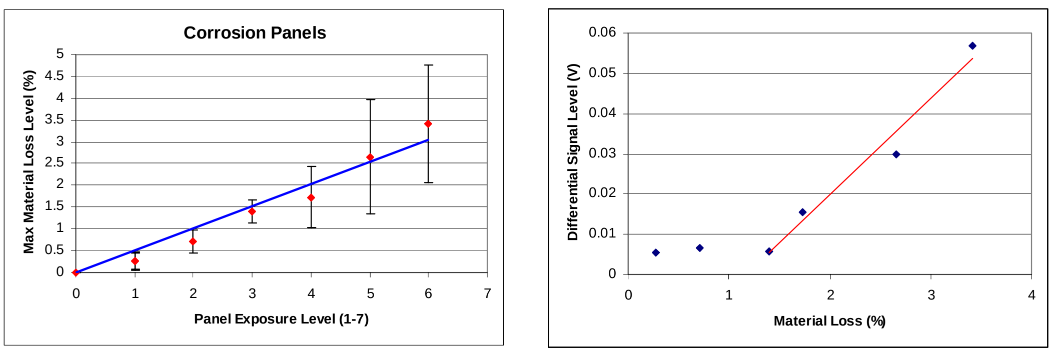


Figure 6. a) Raw signals for increasing damage size (hole radius), b) differential signals, c) percent change in raw signal levels for increasing damage size, and d) differential signal-to-noise level for three different drive frequencies and for increasing damage size.

The results in Figure 6 show an improvement in signal-to-noise ratio (SNR) for the differential measurement case relative to the small notch feature results provided in Figure 5. The SNR = 2 level was approached for a hole feature of approximately 500 microns in diameter, and increased to over 20 for a damage feature with a diameter of 6.3mm. The basic trend in SNR for three different drive frequencies (100kHz, 200kHz, and 300kHz) was nearly linear as shown in Figure 6d. A nominal change (reduction) in the raw signal levels of 1-7% was also noticed for increasing damage feature sizes as depicted in Figure 6c even though the raw overlayed signals in Figure 6a show very little change in their form.

One final measurement was made in-situ for the salt-fog exposure sample depicted in Figures 4a and 4b. The results of this study are provided in Figure 7. For a 3-month salt-fog exposure, corrosion material loss levels were observed in the unprotected, masked-off region of 1%-2.5% representing corrosion pitting levels of only 25-30 microns over an area of ~25cm x 25cm. The sensor spacing in this case was ~250 mm for six sensors with the corrosion feature on the opposite side of the panel centered between the six sensors. As shown in Figure 7b, the differential measurement was capable of discerning corrosion material loss levels between 1-2%, which is a typical target level for most aerospace NDE measurement needs.



a) b)

Figure 7. a) Material loss levels for salt-fog exposure corrosion panel, and b) in-situ differential sensing of corrosion damage.

CONCLUSIONS

One of the most appealing in-situ sensing methodologies for detecting cracks and corrosion in aerospace systems involves the use of piezoelectric sensor arrays. The use of guided-wave ultrasound in thin-skinned aluminum structures, for example, has significant potential for near-term implementation. A key question which needs to be addressed with regard to damage sensing using guided-wave ultrasound in realistic aircraft structures involves the detection sensitivity levels for cracks and corrosion. In this research effort, a systematic evaluation of the detection sensitivity levels of surface-bonded piezoelectric sensor arrays was accomplished using experimental studies and analytic modeling. A series of reference standards were developed for variations in crack/corrosion sizes and types from micron to millimeter scales. Both engineered and realistic crack/corrosion conditions were studied for phased-array and distributed-array sensing approaches. In-situ damage initiation and growth studies

were also conducted using dynamic fatigue crack and electrochemical corrosion attack damage mechanisms. Preliminary results are presented for evaluating current detection sensitivity levels, where opportunities for improving the fidelity, quantification, and damage growth rates in realistic aircraft structures are also considered.

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